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3ARM: A FAST, ACCURATE RADIATIVE TRANSFER MODEL FOR USE IN CLIMATE MODELS

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ABSTRACT

A new radiative transfer model combining the efforts of three groups of researchers is discussed. The model accurately computes radiative transfer in a inhomogeneous absorbing, scattering and emitting atmospheres. As an illustration of the model, results are shown for the effects of dust on the thermal radiation.

1. INTRODUCTION

Researchers at NASA Ames Research Center, Atmospheric and Environmental Research Inc. and Pennsylvania State University have collaborated to produce a fast, accurate radiative transfer model (called 3ARM) for use in climate models. The model combines an existing two stream K distribution code (Toon et al. 1989) with the new K distributions developed by AER (Mlawer et al. 1996) and a four stream option for greater accuracy.

2. DESCRIPTION OF THE MODEL

2.1. The Toon- Ackerman 1989 model

In 1989, Toon and co-workers published a comprehensive analysis of the two stream method and its application for radiative transfer calculations (Toon et al.1989). They showed that the two stream method was relatively accurate for a large number of applications of of interest to atmospheric studies. The model that they developed has been used in a number of climate model applications (e.g. Sahara dust transport - Westphal et al. 1988, Pinatubo aerosol transport -Young et al. 1994, Stratus cloud modeling - Ackerman et al 1993).

The original model had 26 wavelength intervals in the solar and 18 in the infrared. Within each band absorption coefficients accounted for the effects of water vapor, carbon dioxide, ozone and molecular oxygen, resulting in 77 solar intervals and 71 infrared intervals. Scattering, absorption and emission of aerosols and clouds was treated with the two stream approximation as discussed in Toon et al. (1989).

The speed of the code was shown to be comparable to other less accurate codes used in climate models (Toon et al. 1989).

2.2. The AER K distributions

Recently, Mlawer et al. (1996) have developed a set of K distributions to accurately compute the fluxes and cooling rate for the long wave spectral region (10-3000 cm^{-1}) for an arbitrary clear atmosphere.

Comparison of the predicted values with the new K distributions with line by line calculations is very good, as discussed in Mlawer et al. (1996). The long wave accuracy for any atmosphere is 0.6 W m^{-2} for net flux in each spectral band at all altitudes, with a total (10-3000 cm^{-1}) error of less than 1.0 W m^{-2}. At any altitude, the error is 0.07 K d^{-1} for the total cooling rate in the troposphere and lower stratosphere and 0.75 K d^{-1} in the upper stratosphere and above.

We have used the K distributions from Mlawer et al.(1996) to replace the old K values in the model of Toon et al (1989). The resulting model has 16 bands in the infrared with 16 k values for each band. Therefore the model has 256 infrared intervals.

We compared the results of the new model to the SPECTRE data (Ellingson and Wiscombe, 1996). The results are as shown in Table 1.

Table 1
The downward flux at the surface for the 550-2600 cm^{-1} range for the SPECTRE experiment (in mW/m^2-str-cm^{-1}):

Case No	Calculated	Observed
1	24.645	24.803
2	18.1547	18.5883
3	14.929	15.347
4	17.61	18.1156

The comparison to the SPECTRE observations is discussed more fully in Mlawer et al. (1996). The results are considered to be quite good.

2.3. The two stream/four stream option

We have included an option in the model to use a four stream method for greater accuracy if needed. The four stream method follows that discussed in Liou et al. (1988). The difference in accuracy ibetween the two stream and the four stream methods is discussed in Liou (1980), Liou et al. (1988) and Zhu and Arking (1994).

In general, the four stream approximation produces errors that are smaller than the two stream approximation by at least a factor of two (Zhu and Arking, 1994). As an example, Table 2 shows the error in the reflection for a two stream and the four stream for an aerosol with asymmetry factor of 0.7 and single scattering albedo of 0.95. The optical depth is 4.0 (Liou, 1980).

Table 2
Relative error in reflectance of an aerosol layer for the two stream and four stream approximations

μ_0	two stream	four stream
0.1	1.58%	-2.43%
0.3	-4.31%	-3.31%
0.5	-4.35%	-1.07%
0.7	0.71%	0.34%
0.9	12.3%	-2.57%

As shown in Table 1, the relative error is not less at every solar angle. Whether or not the four stream approximation should be used is dependent on the accuracy and speed required. Our initial efforts indicate that the four stream method can be up to ten times slower than the two stream method. We are currently exploring improvements in the computational time required by the four stream method (Q. Fu, personal communication).

3. INFRARED EFFECTS OF DUST

Recently, Sokolik and Toon (1996) have shown that dust aerosols could have significant climatic consequences. We have extended their approach show the effects of dust on the thermal spectrum and to illustrate the capabilities of the new model.

We have taken two of the dust models used by Sokolik and Toon (1996). The optical depth (normalized to the value at 900 cm^{-1}) for the two models are shown in Figure 1.

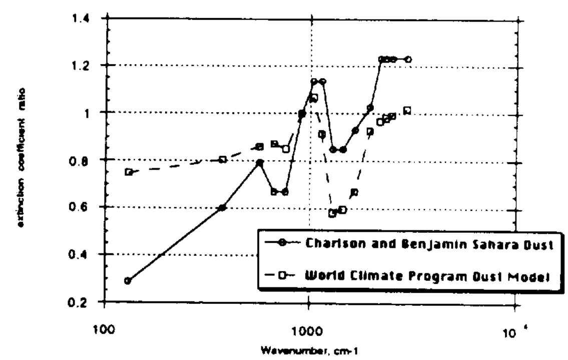

Figure 1: The extinction coefficients for the two dust models.

The single scattering albedo (ω) and asymmetry parameter (g) for the two models are shown in Figure 2.

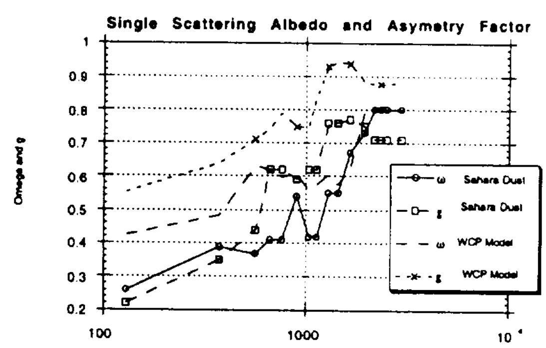

Figure 2. Single scattering albedo and asymmetry parameter for the two dust models.

Using the radiative properties of these two models, we computed the fluxes for a mid latitude summer standard atmosphere. We assumed that the dust was uniformly distributed in the first four km of the atmosphere above the surface.

The change in the net flux at the top of the atmosphere is shown in Figure 3.

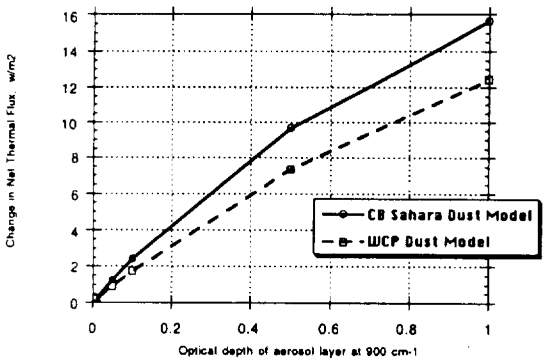

Figure 3: Change in the net flux at the top of the atmosphere as a function of dust optical depth.

The results show that the net effect of the dust (radiative forcing) is warming. That is, the dust acts very much like a greenhouse gas. Analysis of the effects on a spectral basis show that the effect is primarily in the 8-12 μm region.

The change in the downward thermal flux at the surface is shown in Figure 4.

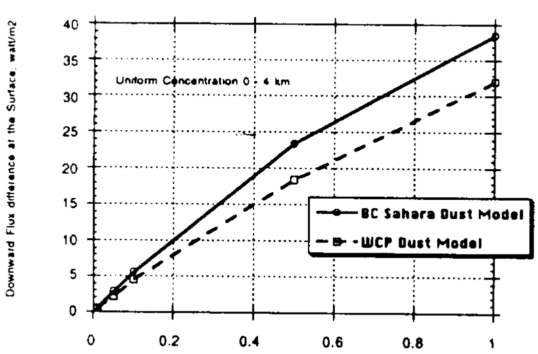

Figure 4: The change in the downward flux at the surface as a function of the dust optical depth.

The results in Figure 4 show that the dust increases the thermal flux at the surface. Again this is similar to the effect of the so-called greenhouse gases.

The effect of dust on the heating rates for one of the dust models for two different vertical distributions are shown in Figure 5.

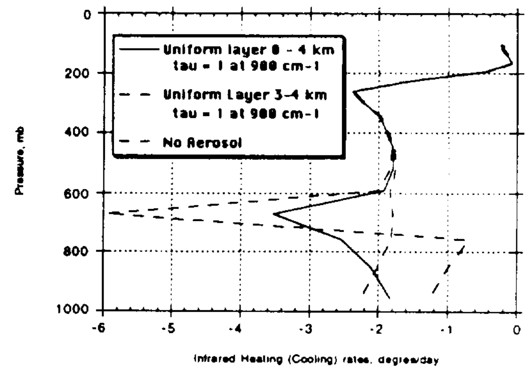

Figure 5: The heating rates for no dust and for two different vertical distributions.

The results in Figure 5 show that the heating rate is very sensitive to the vertical distributions (i.e. thickness of the layer at the same optical thickness).

4. CONCLUSIONS

We have developed a new radiative transfer model for use in climate models by combining the work of three different groups of researchers. The resulting code appears to be fast and accurate and should be useful to the research community. Work is continuing in developing a set of solar K distributions and speeding up the four stream method. We are also working on comparing the model results to observed data.

We have shown that the infrared effects of dust aerosols in the thermal spectral can be significant. Further work is proceeding to determine the local radiative forcing for different geographical regions.

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